

# THE SUPERLUMINOUS SN DES13S2CMM AS A SIGNATURE OF A QUARK-NOVA IN A HE-HMXB SYSTEM

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## ABSTRACT

We show that by appealing to a Quark-Nova (the explosive transition of a neutron star to a quark star) occurring in an He-HMXB system we can account for the lightcurve of the first superluminous SN, DES13S2cmm, discovered by the Dark-Energy Survey. The neutron star's explosive conversion is triggered as a result of accretion during the He-HMXB second Common Envelope phase. The dense, relativistic, Quark-Nova ejecta in turn energizes the extended He-rich Common Envelope in an inside-out shock heating process. We find an excellent fit (reduced  $\chi^2$  of 1.09) to the bolometric light-curve of SN DES13S2cmm including the late time emission, which we attribute to Black Hole accretion following the conversion of the Quark Star to a Black hole.

*Subject headings:* circumstellar matter stars: evolution stars: winds, outflows supernovae: general supernovae: individual (SN DES13S2cmm)

## 1. INTRODUCTION

DES13S2cmm is the first confirmed superluminous SN (SLSN) from the Dark Energy Survey (Papadopoulos et al. (2015)). Its bolometric light-curve (LC) shows a slowly declining tail when compared to other SLSNe. It also shows an initial hump (the first four data points prior to the peak; see Figure 1). Papadopoulos et al. (2015) explored two possible power sources ( $^{56}\text{Ni}$  decay and magnetar spin-down power) but both models poorly fit the LC. In this paper we show that a Quark-Nova (QN) occurring in a Helium-High-Mass X-ray binary (He-HMXB), which experiences a second common envelope (CE) phase, can account for the LC features of SN DES13S2cmm including the tail. The paper is organized as follows: in §2 we give a brief overview of the QN model and the occurrence of QNe in binary systems. In §3 we show the results of applying the QN in a He-HMXB system to SN DES13S2cmm. We provide a brief discussion and some predictions in §4.

## 2. QUARK NOVA (QN) MODEL

The QN is the explosive transition of a neutron star (NS) to a quark star (QS) (Ouyed et al. 2002). The conversion energy combined with the core collapse of the parent NS results in the ejection of  $M_{\text{QN}} \sim 10^{-3} M_{\odot}$  of neutron-rich material (Keränen et al. 2005; Ouyed & Leahy 2009; Niebergal et al. 2010). This relativistic ejecta has a kinetic energy,  $E_{\text{QN}}$ , exceeding  $10^{52}$  erg and an average Lorentz factor  $\Gamma_{\text{QN}} \sim 10$ . The QN can occur following the explosion of a massive single star or in a binary system following accretion from the companion. The key constraint is for the NS to reach deconfinement densities in its core by becoming massive enough (e.g. via fall-back during the SN explosion or accretion from a companion) or via spin-down (Staff et al. 2006). We define  $M_{\text{NS,c}}$  as the NS critical mass above which quark deconfinement occurs in the NS triggering the QN (see Ouyed et al. (2013a) for a recent review).  $M_{\text{NS,c}}$  varies from  $\sim 1.6M_{\odot}$  up to  $2M_{\odot}$  and higher for different equations of state (e.g. Staff et al. 2006). However we assume  $M_{\text{NS,c}} = 2M_{\odot}$  to account for the recent heavy NS observed by Demorest et al. (2010);  $\sim 2M_{\odot}$  (or heav-

ier) quark stars can exist when one considers interacting quarks (e.g. Alford et al. 2007).

### 2.1. QNe in single-star systems: dual-shock QNe

A dual-shock QN (dsQN) happens when the QN occurs days to weeks after the initial SN. The delay allows the QN ejecta to catch up to and collide with the SN ejecta after it has expanded to large radii (Leahy&Ouyed 2008; Ouyed et al. 2009). The SN provides the material at large radius and the QN re-energizes it, causing a re-brightening of the SN. For time delays of days or less, the radius of the SN ejecta is small enough that only a modest re-brightening results when the QN ejecta hits the SN ejecta. However, the neutron-rich QN ejecta lead to unique nuclear spallation signatures (Ouyed et al. 2011a). For longer time-delays, the radius and density of the SN ejecta are such that extreme re-brightening is observed which could explain some SLSNe (Ouyed et al. 2012; Kostka et al. 2014; Ouyed & Leahy 2013). For time-delays exceeding many weeks, the SN ejecta will be too large and diffuse to experience any re-brightening. The dsQN model has been successfully applied to a number of superluminous and double-humped supernovae (see <http://www.quarknova.ca/LCGallery.html> for a picture gallery of the fits).

### 2.2. Quark-Novae in binary systems

A QN will more often occur in tight binaries. To reach  $M_{\text{NS,c}}$  and experience a QN event, the NS needs to accrete from a Roche Lobe (RL) overflowing companion (Ouyed et al. 2011b&c; Ouyed & Staff 2013; see also Ouyed et al. 2015) or during a CE phase of the binary as described in this work. A QN in a binary provides:

(i) A means (the relativistic QN ejecta) to shock, compress, and heat the NS companion or the CE. In the case of a QN occurring inside a CE (which is considered in this paper), the resulting envelope thermal energy is given by  $E_{\text{CE,th.}} = \zeta_{\text{sh.}} E_{\text{QN}}$  which yields an initial shock temperature  $T_{\text{QN,sh.}} \sim \zeta_{\text{sh.}} \times 10^9 \text{ K} \times E_{\text{QN,52}} \times (M_{\odot}/M_{\text{CE}})$  for a He-rich envelope of mass  $M_{\text{CE}}$  and mean molecular weight  $\mu_{\text{CE}} = 4/3$ ;  $E_{\text{QN,52}}$  is the QN kinetic energy in units of  $10^{52}$  ergs while  $\zeta_{\text{sh.}}$  is the shock heat-

ing efficiency. The CE kinetic energy is found from  $E_{\text{QN}} = E_{\text{CE,K}} + E_{\text{CE,th.}}$  where the CE thermal energy is  $E_{\text{CE,th.}} = E_{\text{CE,gas}} + E_{\text{CE,rad.}}$ , shared between the gas and the radiation. We find that even for extreme shock efficiency  $\zeta_{\text{sh.}} \sim 1$  and for high compression ratio ( $\sim 4\Gamma_{\text{QN}} \sim 40$ ; see Ouyed&Staff 2013), the timescale required to burn He to O (e.g. using burning rates from Huang & Yu (1998)) is too large compare to the adiabatic expansion timescale of the CE.

(ii) The spin-down power from the QN compact remnant (the QS), which provides an additional energy source. The QS is born with a magnetic field of the order of  $10^{15}$  G due to color ferromagnetism inherent to quark matter during the transition (Iwazaki 2005). In the scenario considered here where the QS accretes during a CE phase, the high accretion rates would lead to QS spin-up instead of spin-down and the QS would gain mass until it becomes a BH without entering a spin-down phase. Thus in the picture presented here, spin-down power can be ignored.

(iii) The presence of a gravitational point mass (the QS) which may slow down and trap some of the ejecta and provide accretion power (e.g. Ouyed et al. 2011b&c; Ouyed et al. 2014; Ouyed et al. 2015). The conversion of the QS to a BH during the CE phase provides an additional source of energy (the BH-accretion phase) which powers the LC in addition to energization by the QN shock.

### 2.2.1. The Quark-Nova in a He-HMXB system

In previous papers we considered the detonation of a CO White Dwarf by the QN (what we called a QN-Ia; Ouyed&Staff 2013; Ouyed et al. 2014; Ouyed et al. 2015). In a QN-Ia, the system experiences a runaway mass transfer leading to the formation of a CO-rich torus surrounding, and in the close vicinity of, the exploding NS. In this paper we consider a QN in a He-HMXB. Such a binary is expected to form when an O/B-HMXB binary evolves through a CE phase of the supergiant stellar component. If the binary survives this first CE event, the resultant system would contain a He-rich core (Hall& Tout 2014) with a NS in a relatively tight orbit. For a large mass ratio<sup>1</sup>  $q$ , a runaway mass transfer is expected once the He-rich core overflows its RL leading to the onset of a second CE phase<sup>2</sup>. The NS accretes from two mass reservoirs (the first CE and the second CE). For a NS born with an initial mass of  $\sim 1.6M_{\odot}$ , accretion of  $\sim 0.4M_{\odot}$  during the two CE phases is necessary to drive it above  $M_{\text{NS,c.}}$ ; accreting  $\sim 0.2M_{\odot}$  of material per CE phase is not unreasonable and should be enough to eject the first CE (Brown (1995); Armitage & Livio (2000)). If the in-spiralling NS accretes enough mass during the second CE phase, it should drive the NS above  $M_{\text{NS,c.}}$  to undergo a QN explosion in an extended CE; the CE expands radially outward as the NS in-spirals towards

the core. Following the QN explosion the QS continues to in-spiral into the core while gaining mass. Below we show that if the QS turns into a BH, BH-accretion can power the slowly declining tail of DES13S2cmm. A combination of QN shock heating and BH-accretion provides the best fit to DES13S2cmm.

## 3. APPLICATION TO DES13S2CMM

The free parameters in our model are (see Table 1): the CE mass ( $M_{\text{CE}}$ ), its initial (extended) radius  $R_{\text{CE},0}$  at the time of QN shock breakout; the CE expansion velocity  $v_{\text{QN}}$  induced by the QN shock and QN shock heating per particle  $(3/2)k_{\text{B}}T_{\text{QN,sh.}}$ ;  $\alpha_{\text{QN,sh.}}$ , the shock propagation parameter (see Appendix). There are three parameters for the BH-accretion model based on the prescription of Dexter&Kasen (2013) (see their appendix A):  $L_0$  ( $\text{erg s}^{-1}$ ),  $y_0$  and  $n$  which together define the injection power  $L(t) = L_0(t/t_0)^{-n}$  with  $t_0 = y_0 t_{\text{d}}$  and  $t_{\text{d}}$  the photon diffusion time in the CE; BH-accretion turns on at  $t = t_0$  so that  $L(t) = 0$  for  $t < t_0$ . Table 1 shows the model's best-fit parameters for the BH-accretion model alone and the for the two-component QN+BH-accretion model. The best-fits reduced  $\chi^2$  values are given in the last column of the table.

### 3.1. BH-accretion fit

This model does not have the QN explosion if the NS experiences a transition to a BH directly while the system is in the second CE phase. The NS could turn into a BH prior to or during merging with the CE core which forms an accretion disk around the BH to power the LC. The best-fit is obtained for  $t_{\text{d}} = 13.7$  days,  $y_0 = 0.1$  (i.e.  $t_0 = 5.6$  days),  $L_0 = 6 \times 10^{44} \text{ erg s}^{-1}$  and  $n = 0.7$ . The fit is shown in Figure 1 along-side the observations from Papadopoulos et al. (2015). The resulting best-fit reduced  $\chi^2_{\text{red.}}$  is  $\sim 2.77$ . The initial hump is not well fit with this model.

### 3.2. QN+BH-accretion fit

Adding the QN shock heating yields a significant improvement in the LC fit with a reduced  $\chi^2_{\text{red.}}$  of  $\sim 1.09$  (see Table 1). The BH-accretion phase is delayed from the QN event by the time required for the QS to turn into a BH, merge with the core and trigger accretion. This time delay is  $t_0$  at which point the CE has extended to a radius  $R_{\text{CE},0} + v_{\text{QN}}t_0$ ;  $R_{\text{CE},0}$  is the CE radius at QN shock breakout (see Appendix). The LC fit of DES13S2cmm is shown in Figure 2 along-side the observations from Papadopoulos et al. (2015).

The QN shock energizes the He CE (of mass  $M_{\text{CE}} = 2M_{\odot}$  and radius  $R_{\text{CE},0} = 1350R_{\odot}$ ) and yields the initial bright and short-lived hump; the corresponding initial CE temperature  $T_{\text{CE},0}$  is calculated from the QN shock heating ( $T_{\text{QN,sh.}} = 3.7 \times 10^6 \text{ K}$ ; i.e.  $\zeta_{\text{sh.}} \sim 10^{-2}$  for  $M_{\text{CE}} = 2M_{\odot}$ ) by including radiation energy density (see Appendix). The photon diffusion timescale is  $t_{\text{d}} = (2/3)\sqrt{M_{\text{CE}}\kappa_{\text{Th.}}/(0.3\beta cv_{\text{QN}})} = 12.6$  days with  $\beta = 13.8$  (Arnett (1982));  $c$  is the speed of light and  $\kappa_{\text{Th.}}$  the Thompson cross-section.

## 4. DISCUSSION AND CONCLUSION

In this paper we showed that the LC of SN DES13S2cmm is best fit with the QN+BH-accretion

<sup>1</sup> E.g.  $q > 3.5$  or orbital period  $P_{\text{orb.}} < 0.1$  days (Ivanova et al. 2003). Alternate conditions leading to a second CE phase give  $2.4 \leq q \leq 2.7$  and  $P_{\text{orb.}} < 0.25$  days (Dewi & Pols 2003). See Tauris et al. (2015) for other outcomes and for a recent investigation of the evolution of these systems.

<sup>2</sup> In Ouyed et al. (2015), where the NS companion is a degenerate WD, the runaway accretion is due to companion expansion (since  $R \propto M^{-1/3}$ ) which leads to high-density (degenerate) torus formation.

TABLE 1  
BEST-FIT PARAMETERS FOR THE DES13S2CMM LC IN OUR MODEL.

	He-rich (i.e. second) CE		QN			BH Accretion				Fit
	$M_{\text{CE}} (M_{\odot})$	$R_{\text{CE},0} (R_{\odot})$	$v_{\text{QN}} (\text{km/s})$	$T_{\text{QN,sh.}} (\text{K})$	$\alpha_{\text{QN,sh.}}$	$t_d (\text{days})$	$y_0$	$L_0 (\text{erg/s})$	$n$	$\chi^2_{\text{red}}$
BH-accretion	—	—	—	—	—	13.7	0.10	$6 \times 10^{44}$	0.7	2.77
QN+BH-accretion	2	1350	40,000	$3.7 \times 10^6$	3/2	— <sup>†</sup>	0.45 <sup>††</sup>	$2.8 \times 10^{44}$	0.8	1.09

<sup>†</sup> Here,  $t_d$  is given by  $t_d = (2/3)\sqrt{M_{\text{CE}}\kappa_{\text{th}}/(0.3\beta cv_{\text{QN}})} = 12.6$  days. <sup>††</sup> This corresponds to  $t_0 = y_0 t_d \simeq 5.6$  days.  
The kinetic energy of the CE/ejecta after the QN is  $E_{\text{CE,K}} = (1/2)M_{\text{CE}}v_{\text{QN}}^2 \simeq 3.2 \times 10^{52}$  ergs.

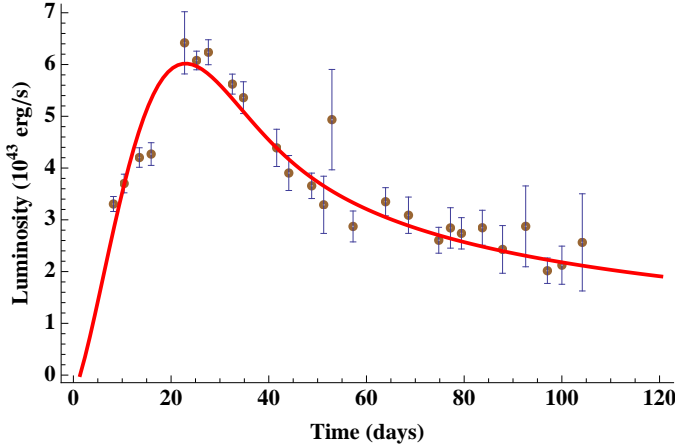


FIG. 1.— The BH-accretion model fit (solid line) to the light curve of SN DES13S2cmm. The observations (the solid circles and the error bars) are from Papadopoulos et al. (2015).

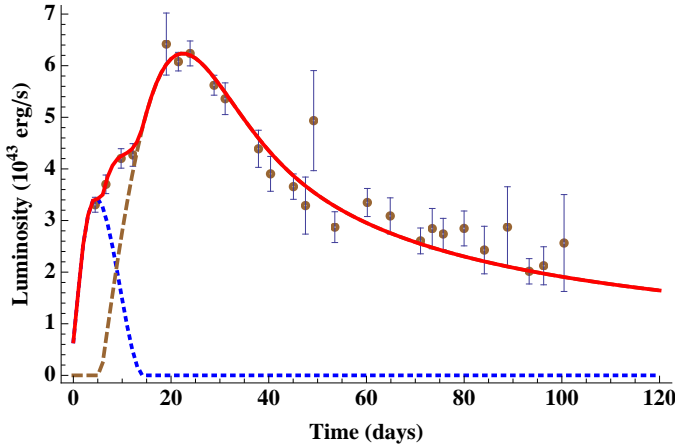


FIG. 2.— The QN+BH-accretion model fit (solid line) to the light curve of SN DES13S2cmm.

model. In our model, the QN occurs during the second CE phase of He-HMXB system followed by a BH-accretion phase after the QS turns into a BH in the core of the CE. The QN shock re-energizes the extended CE explaining the initial hump while BH-accretion power nicely fits the slowly declining tail. No nuclear burning is triggered by the QN shock which means that there should be little or no He-burning products in SN DES13S2cmm and similar explosions.

The lack of He-HMXB systems when compared to the observed large population of HMXBs with Be-type stars (e.g. Raguzova & Popov (2005) and reference therein)

has been used as an observational argument in favor of mergers during the dynamically unstable mass transfer phase of the progenitors (e.g. Linden et al. 2012; see also van den Heuvel 1976). However, even in extreme cases, the theoretically predicted fraction of He-HMXBs surviving the CE phase is still higher than the observed number (Linden et al. 2012). If the NS is born massive, it will likely accrete enough matter during the first CE phase to reach  $M_{\text{NS,c.}}$ . The resulting QN could remove enough matter to unbind the system and bypass the production of He-HMXBs. We thus speculate that the QN may be partly responsible for the rarity of He-HMXBs.

If the NS does not accrete enough mass to go QN in the second CE phase, it may reach the center and form a Thorne-Żytkow object (Thorne & Żytkow (1977)). However, continued accretion should trigger a QN leading to the same outcome. I.e. Thorne-Żytkow objects could be short-lived. On the other hand, extreme accretion rates could turn the NS directly into a BH.

The idea of a QN in binaries has proven successful in accounting for some features of SNe-Ia (Ouyed et al. 2014; Ouyed et al. 2015) and Gamma Ray Bursters (Ouyed et al. 2011c) and has been able to account for the LC of DES13S2cmm as shown here. Its ability in fitting properties of unusual SNe (see <http://www.quarknova.ca/LCGallery.html>) suggest that QNe may be an integral part of binary evolution; the QN could lead to novel and interesting evolutionary paths. Nevertheless, as we have stated before, our model relies on the feasibility of the QN explosion which requires sophisticated simulations of the burning of a NS to a QS which are being pursued. Preliminary simulations with consistent treatment of nuclear and neutrino reactions, diffusion, and hydrodynamics show instabilities that could lead to a detonation (Niebergal et al. 2010; see also Herzog & Röpke (2011) and Albarracín Manrique & Lugones (2015)). We have already argued that a “core-collapse” QN could also result from the collapse of the quark matter core (Ouyed et al. 2013a) which provides another avenue for the QN explosion.

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## APPENDIX

Due to the outward diffusion of photons, the photosphere is moving inward in mass coordinates, slowly at first but faster as the density decreases in time. The ejecta interior to the photosphere we refer to as the core. We will assume that the thermal energy in the exposed mass in the photosphere (as the cooling front creeps inward) is promptly radiated. The interplay between uniform expansion and radiation diffusion defines the evolution of the photosphere as

$$R_{\text{phot.}}(t) = R_{\text{CE}}(t) - D(t), \quad (1)$$

where  $R_{\text{CE}}(t) = R_{\text{CE},0} + v_{\text{QN}}t$  and  $R_{\text{CE},0}$  the CE envelope radius at QN shock breakout (which corresponds to  $t = 0$  in our model). Here  $D(t)$  is the diffusion length

$$D(t)^2 = D_0^2 + \frac{c}{n_{\text{CE}}(t)\sigma_{\text{Th}}}t, \quad (2)$$

where  $n_{\text{CE}}(t) = N_{\text{CE}}/V_{\text{CE}}(t)$  is the number density in the CE. The total number of particles in the CE is  $N_{\text{CE}} = (M_{\text{CE}}/\mu_{\text{CE}}m_{\text{H}})$  while  $V_{\text{CE}}(t) = (4\pi/3)R_{\text{CE}}(t)^3$  is the volume extended by the CE and  $m_{\text{H}}$  the Hydrogen atomic mass. We define  $D_0$  as the initial diffusion length scale by setting  $n_{\text{CE},0}\sigma_{\text{Th}}D_0 \simeq 1$  where  $n_{\text{CE},0} = N_{\text{CE}}/V_{\text{CE},0}$  and the initial volume  $V_{\text{CE},0} = (4\pi/3)R_{\text{CE},0}^3$ .

The initial QN shock heating per particle  $(3/2)k_{\text{B}}T_{\text{QN,sh.}}$  is a free parameter;  $k_{\text{B}}$  is the Boltzmann constant. The heat is redistributed between gas and radiation to get the post-shock CE temperature  $T_{\text{CE},0}$ . The relevant equation is  $\frac{3}{2}k_{\text{B}}n_{\text{CE},0}T_{\text{CE},0} + a_{\text{rad}}T_{\text{CE},0}^4 = \frac{3}{2}k_{\text{B}}n_{\text{CE},0}T_{\text{QN,sh.}}$ , with  $n_{\text{CE},0}$  the number density (of electrons and ions) and  $a_{\text{rad}}$  the radiation constant.

The subsequent evolution of the CE core temperature after the CE is fully shocked is given by  $T_{\text{core}}(t) = T_{\text{CE},0}(R_{\text{CE},0}/R_{\text{CE}}(t))^{2-\alpha_{\text{QN,sh.}}}$ . To account for a non-uniform initial temperature, we introduce  $\alpha_{\text{QN,sh.}}$  which parameterizes complex shock physics beyond the scope of this work.  $\alpha_{\text{QN,sh.}} = 0$  corresponds to the case of an adiabatic expansion with spatially uniform initial  $T_{\text{CE},0}$ . I.e. the internal energy includes only gas internal energy with  $\gamma = 5/3$ , so as time increases,  $T_{\text{core}}(t) \propto R_{\text{CE}}(t)^{-2}$ .  $\alpha_{\text{QN,sh.}}$  also allows to account for the presence of radiation, e.g. for spatially uniform  $T_{\text{CE},0}$  and  $\gamma = 4/3$ , one uses  $\alpha_{\text{QN,sh.}} = 1$ .  $\alpha_{\text{QN,sh.}} > 0$  also can correspond to a radially decreasing initial CE temperature so that  $T_{\text{core}}$  decreases more slowly than it would be for uniform  $T_{\text{CE},0}$ .

The corresponding luminosity is

$$L_{\text{QN}}(t) = c v_{\text{tot.}}(t) \Delta T_{\text{core}}(t) n_{\text{CE}}(t) 4\pi R_{\text{phot.}}(t)^2 \frac{dD(t)}{dt}, \quad (3)$$

where the total specific heat is  $c v_{\text{tot.}}(t) = c v_{\text{gas}} + c v_{\text{rad.}} = \frac{3}{2}k_{\text{B}} + \frac{a_{\text{rad}}T_{\text{core}}(t)^3}{n_{\text{CE}}(t)}$ . Here,  $\Delta T_{\text{core}} \sim T_{\text{core}}$  since the photosphere cools promptly (i.e. cooling time is much less than the diffusion timescale). The inward photospheric velocity in mass coordinates is  $dD(t)/dt$ . When  $n_{\text{CE}}(t)$  is low, the  $T^3$  term dominates so that the temperature is much lower than in the pure gas model. As  $n_{\text{CE}}(t)$  increases, the gas energy density becomes more important and  $T$  rises.